From the Paddock to the Stream – Unravelling the Nitrogen Flowpaths in a New Zealand Dairying Catchment

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– Unravelling the Nitrogen Flowpaths in a New Zealand Dairying Catchment

Roland Stenger, Greg Barkle[1], Vince Bidwell, Craig Burgess[2], Aaron Wall, Markus Haas, and Jan Mertens

Lincoln Environmental Research, Private Bag 3062, Hamilton, NZ; PH ++64 7 858 4844; FAX ++64 7 858 4844; email: stenger@lvlham.lincoln.ac.nz

[1] now: Aqualinc Research Limited, PO Box 14041, Hamilton, NZ

[2] now: Earth Science Department, University of Waikato, Hamilton, NZ

Abstract

The Toenepi catchment (15 km^2) is dominated by dairying, and ranges in elevation from 40 to 130m above sea level (ASL). Most of the catchment is flat land, with some rolling and steep land occurring on the boundaries. Annual rainfall is 1132 mm and mean annual temperature is 13.3°C. Well-drained Allophanic soils dominate in the catchment in close association with granular soils of moderate permeability. Poorly drained Gley soils occur in the lowest areas adjacent to the stream and require artificial drainage. The average stocking rate is 3.0 cows ha^{-1}, which graze all year. The catchment export of total nitrogen through the stream had been calculated in an earlier project as 35 kg ha^{-1} yr^{-1}. The median total nitrogen concentration in the stream was 3 mg L^{-1} (1995/97). To better understand nitrogen flowpaths, we initially installed groundwater monitoring transects in seven subcatchments, which reflected the major site and landuse conditions. Monthly sampling indicated that the concentrations of inorganic nitrogen in the shallow groundwater were generally well below the concentrations measured in the stream. This result would not support the hypothesis that the majority of the nitrate in the stream is derived from groundwater. Monitoring of the nitrogen concentrations in drains indicated that artificial drainage may be a major conduit for nitrogen into the stream. Artificial drains bypass the deeper subsoil and riparian zones where denitrification is likely to occur. A mathematical groundwater discharge model is used to quantify the proportion of streamflow that can be explained by groundwater discharge in contrast to near-surface flowpaths (surface runoff, artificial drainage). Understanding the pathways through which nitrogen enters Toenepi Stream is considered a prerequisite for the development of the most effective and efficient measures to reduce the N contamination of the stream.

Introduction

Since 1995, researchers from different organisations have investigated environmental effects of dairying in the Toenepi catchment, particularly focusing on surface water quality. The catchment is drained by Toenepi Stream, which has been monitored intensively by researchers from the National Institute for Water and Atmospheric Research (NIWA) and has been shown to have poor water quality due to elevated nutrient levels and faecal pollution. Total nitrogen (TN) exports through Toenepi Stream have been reported as 35.0 kg ha^{-1} yr^{-1} in 1995/97 and as 21.5 kg ha^{-1} yr^{-1} in 2001/02. In both periods, inorganic nitrogen (IN = NO_x-N + NH_4-N) accounted for more than 80% of the total nitrogen (Wilcock and Duncan, 2003). Annual flow-averaged concentrations were similar for both periods; 5 to 6 mg L^{-1} for total nitrogen and 4 to 5 mg L^{-1} for nitrate plus nitrite nitrogen (NO_x-N). These values are markedly higher than the medians of all samples taken, as NO_x-N and TN concentrations were found to increase with increasing stream flow (Wilcock et al., 1998), which results in highly skewed data sets. Median concentrations for the 2001-2002 period have been reported as 0.05 mg L^{-1} NH_4-N, 1.78 mg L^{-1} NO_x-N, and 2.82 mg L^{-1} TN (Wilcock and Duncan, 2003).

A good understanding of the pathways through which nitrogen enters Toenepi Stream is a prerequisite for the development of improved land use practises that result in lower contamination of the stream. Given that Toenepi Stream flows all year round, groundwater is obviously the main source of the streamflow and thus potentially also of the nitrogen entering the stream. Apart from groundwater discharge, artificial drainage, which is required for successful farming in many low-lying areas of the catchment, could be a major pathway (Monaghan et al., 2002; Wilcock et al., 1999). Apart from these non-point sources, there are also point-sources to consider, particularly effluent collected in the farm dairy and associated holding pads during milking. In contrast to the now prevailing effluent-irrigation onto land, 80% of the dairy farmers in the catchment still discharge effluent after 2-pond treatment into surface waters. Direct stock access to surface waters still does occur to some extent, but together with surface runoff is not considered to be a major pathway for N from the paddock to the stream.

In 2002, Lincoln Environmental began the still ongoing work in the catchment. Through a combination of monitoring, experimentation and modelling, we are working towards the quantification of the different pathways through which N reaches Toenepi Stream.

Catchment characteristics

The Toenepi catchment spans a range of physical conditions and land use intensities that is reflected in the monitoring scheme developed. The catchment comprises 15.1 km^2, ranging in elevation from approx. 40 to 130m above mean sea level. Most of the catchment is flat land (89%), with some rolling land (10%) and steep land (1%) occurring predominantly on the boundaries (Fig. 1).

ArcView was used to delineate twenty-nine subcatchments based on their topography. Three major soil groups are found in the catchment. Poorly drained Topehaehae soils (Gley Soils) have a narrow distribution and generally occur in the lowest areas adjacent to the main stream and in valleys between hills. The very similar Kereone and Kiwitahi soils (Allophanic Soils) occur on easy rolling to rolling slopes and on freely drained levees of the plain. These allophanic soils with good soil physical properties account for 47% of the soils in the catchment. Morrinsville soils (Granular Soils), which occur in close association with the former group on low rolling downland topography, make up the remaining 40%. These soils generally have high subsoil clay contents, resulting in only medium bulk density, porosity and macroporosity and moderate permeability (Wilson, 1980). In 2002, dairy farms accounted for 21 out of the 26 farms in the catchment, with the remainder being beef, sheep or mixed farms. Stocking density for all farms was calculated from the farm survey data in 2001 (Muirhead et al., 2002).

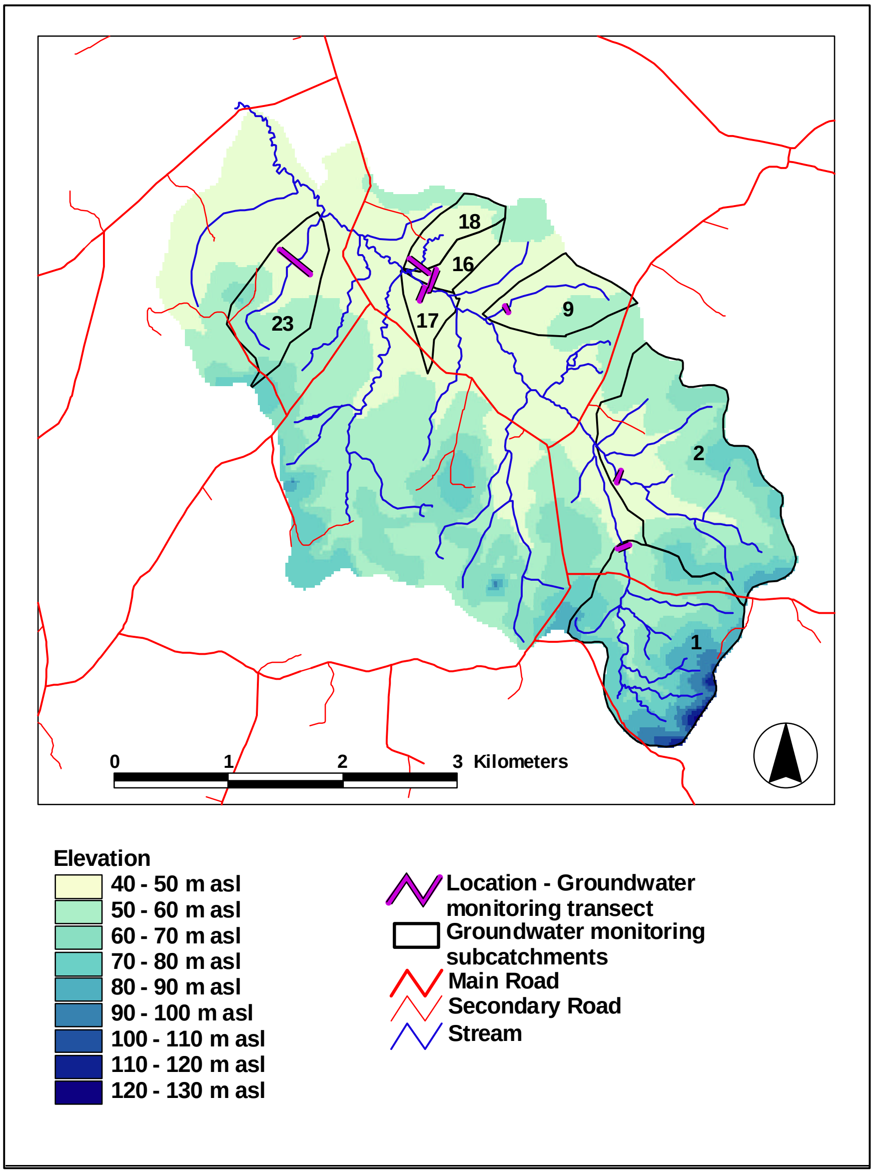

Figure 1. ***Toenepi catchment; numbers indicate the seven subcatchments selected for groundwater monitoring.***

Seven out of the 29 delineated subcatchments (SC) were selected to represent the major site and land use patterns occurring in the catchment (Table 1). For further detail, the reader is referred to Stenger *et al.* (2004).

Table 1. Characteristics of the seven subcatchments selected for shallow groundwater monitoring.

SC	Area (ha)	Land use	Stocking density	Topography	Predominant soil type
1	164	Mainly dairy	Medium	Diverse	Morrinsville
2	209	Mainly drystock	Low	Mainly flat	Kiwitahi/Kereone
9	52	Dairy	High	Flat	Kiwitahi/Kereone
16	19	Dairy	Medium/High	Flat	Morrinsville and Kiwitahi/Kereone
17	19	Mainly dairy	High	Flat	Topehaehae
18	26	Dairy	Medium/High	Flat	Morrinsville
23	66	Dairy	Medium	Mainly flat	Kiwitahi/Kereone

Groundwater monitoring transects

Groundwater monitoring transects consisting of four to six wells per transect were installed in the seven selected subcatchments (Fig.1), predominantly along fence lines. Topehaehae soils dominate along the well transects in SC2, SC9 and SC17 and are mapped for some well locations close to surface waters in several other subcatchments. While most transects go across different soil types, the well transects in SC16 and SC18 are almost exclusively on Kiwitahi soils.

The PVC pipes used (Class E, 15mm nominal diameter, internal diameter 17.7mm) were slotted over their entire length (slot width 0.45mm). With the exception of wells SC2-3 (3.8m), SC18-4 (4.3m), and SC23-1 (5m), all wells were installed to a depth of 2.5 to 3.0m below the surface using a direct push-probe system (Geonor, Norway). This procedure involved driving a 25mm probe down to the required depth using a percussion hammer, jacking the probe out of the ground and quickly inserting the PVC well down the hole. Pumping of the well until the water became clear developed the wells.

The monitoring wells and adjacent surface waters (Toenepi Stream, tributaries, surface drains) were sampled at monthly intervals. Water levels in the wells were measured on the first day of each sampling, using an acoustic water level meter. Wells were subsequently purged and a 60mL water sample taken on the following day. Samples were chilled in the field and then frozen back in the laboratory prior to analysis for NO_X-N and NH_4-N concentrations following standard laboratory procedures.

Groundwater table

The median depth to the water table of most well transects ranged between one and two meters below ground surface (Dec 2002 – Dec 2004). Shallower median water tables were observed in SC17 (-0.91m) and in SC23 (-0.74m). The deepest median groundwater table was found in SC18 (-2.15m). The monthly recorded groundwater levels in subcatchments 1, 2, 17, and 23 were more dynamic than those in the remaining subcatchments and showed clear minima in February and/or March 2003. No distinct summer minima were observed in 2004 due to unseasonably high rainfall. Groundwater within 50cm of the soil surface was often observed adjacent to surface waters, but in some subcatchments it also occurred further away from the surface water. Artificial drainage near these transects (e.g. SC17) prevents the groundwater table from rising even closer to the surface during periods of high rainfall and low evapotranspiration (i.e. mainly during winter).

Inorganic nitrogen concentrations in groundwater

Inorganic nitrogen concentrations in the vast majority of all groundwater samples were below 1 mg L^{-1} (Table 2), with short-lived higher concentrations predominantly caused by NH_4-N peaks, whereas consistently enhanced concentrations were predominantly caused by high NO_3-N concentrations. NH_4-N peaks in shallow groundwater may be caused by cows urinating close to the well and preferential flow transporting the urine rapidly below the root zone.

Table 2. Concentrations of inorganic nitrogen (mg L^{-1}) in well transects, Dec 2002 – Dec 2004.

Well Transect	Min.	Max.	Median	Mean
SC1	0.00	0.91	0.03	0.11
SC2	0.00	2.49	0.03	0.12
SC9	0.00	5.00	0.32	1.04
SC16	0.00	1.84	0.12	0.40
SC17	0.00	1.22	0.08	0.15
SC18	0.00	10.48	1.50	2.82
SC23	0.00	45.35	0.27	6.92
Overall (n=35)	0.00	45.35	0.14	1.55
Overall, (n=34) SC23-1 excl.	**0.00**	**10.48**	**0.13**	**0.61**

The concentrations of inorganic N in the groundwater were well below the flow-averaged concentrations of 4-5 mg L^{-1} observed in the Toenepi Stream. The nitrogen concentrations in the different transects did not directly reflect the differences in land use intensity (see Table 1); a possibly modifying effect of the different soil types warrants further investigation. The transect in SC18 has relatively high concentrations, which can be attributed to effluent-irrigation onto land. The highest mean concentration of all catchments was 7 mg L^{-1} and was found in the SC23 transect. This high mean is due to one single well that consistently has shown concentrations above 27 mg L^{-1}, whereas none of the adjacent wells has ever exceeded 5 mg L^{-1}. The reasons for these high concentrations are not known. Ignoring this outlier, the median concentration of our groundwater transects was 0.13 mg L^{-1} and the mean 0.61 mg L^{-1}.

Relative to the WHO drinking water guideline of 11.3 mg L^{-1}, the NO_3-N concentrations in the groundwater samples were very low in the majority of all samples, with only well SC23-1 consistently lying well above the critical value. If the current guideline value of 0.15 mg L^{-1} NO_3-N for protecting surface water against excessive growth of nuisance plants and algae (MfE, 2000) is used as reference, the groundwater in four out of the seven transects met this standard at most sampling times (SC1, SC2, SC16, and SC17).

The generally low concentrations found in the transects are surprising, given that Power et al. (2002), using the nutrient budgeting tool OVERSEER, calculated average leachate NO_3-N concentrations leaving the root zone of 8 mg L^{-1} for an average Toenepi dairy farm and up to 20 mg L^{-1} for very high intensity dairy farms. However, subsoil denitrification and denitrification in wetland zones is explicitly discussed as removal mechanisms that are not accounted for by the model. Preliminary analysis of our data would suggest that e.g. the very low concentrations found in the SC17 groundwater transect in spite of the high land use intensity may be due to substantial denitrification occurring in the Gley soil.

Inorganic nitrogen concentrations in subsurface and surface drains

From July 2003 onwards, we supplemented our groundwater monitoring programme with the monitoring of subsurface (SSD) and surface drains (SD).

Table 3. Concentrations of inorganic nitrogen (mg L^{-1}) in subsurface drains (SSD), Jul 2003 – Dec 2004.

Subcatchment	Min.	Max.	Median	Mean
SC1 (n=1)	0.32	10.86	8.85	8.25
SC23 (n=2)	0.79	7.52	3.43	3.36
SC17 (n=7)	0.13	4.04	1.07	1.27
Overall (n=10)	**0.13**	**10.86**	**2.14**	**3.05**

N concentrations in subsurface drains were mainly higher or in the same range as those measured in Toenepi Stream. Table 3 demonstrates the very wide range of concentrations found in subsurface drains. Preliminary analysis would suggest that these differences may be more related to a different degree of denitrification occurring in these three subcatchments, rather than to differences in the land use intensity.

N concentrations in the two monitored surface drains (Table 4) were generally higher than those measured in Toenepi Stream, however, both monitored surface drains were affected by point-sources of N. The generally high concentrations measured in the drain in SC1 can be attributed to discharge from an effluent-treatment pond, as reflected in the observation that ammonium N consistently accounted for 74 to 97% of the inorganic N. Inorganic N concentrations in the surface drain in SC17 were generally somewhat higher in its upper reach compared to where it discharges into Toenepi Stream and consisted predominantly of nitrate N. Recent additional measurements indicate that seepage from an effluent-treatment pond contributes to the N in this drain.

Table 4. Concentrations of inorganic nitrogen (mg L^{-1}) in surface drains (SD), Jul 2003 – Dec 2004.

Subcatchment	**Min.**	**Max.**	**Median**	**Mean**
SC1	1.37	16.11	10.19	9.42
SC17 upper reach	0.30	6.70	4.48	5.28
SC17 end	0.03	5.64	3.19	3.76

Groundwater discharge modelling

N concentrations alone are obviously not sufficient to understand which flowpaths the important ones are. Discharge from effluent-ponds is characterised by high concentrations (typically 90 mg L^{-1} TN), but the flow is very low. Artificial drainage was found to have medium to high concentrations, but its share of the annual water flow may not be very high. Groundwater featured by far the lowest concentrations, but groundwater input is likely to dominate the annual streamflow.

A mathematical groundwater discharge model (Bidwell, 2002) was used to quantify the proportion of streamflow that can be explained by groundwater discharge in contrast to near-surface water flowpaths (surface runoff, artificial drainage).

This approach consists of three components:
a) the recharge estimate derived from an independent soil-water balance model,
b) the average dynamic residence time (T) in the vadose zone, and
c) the dynamic response parameter a of the groundwater discharge model, which encapsulates aquifer bulk properties of hydraulic conductivity k, storativity S, as well as the dimensions of effective aquifer thickness B and length of flow path L. This groundwater discharge model is based on the eigenvalue solution to the dynamic response of an ideal aquifer (e.g., Sloan, 2000).

The maximum drainage rate through the vadose zone D_{max}, T, and a are the only parameters that need to be calibrated. This calibration is done based on preferably long-term streamflow data sets with a high temporal resolution (e.g. hourly).

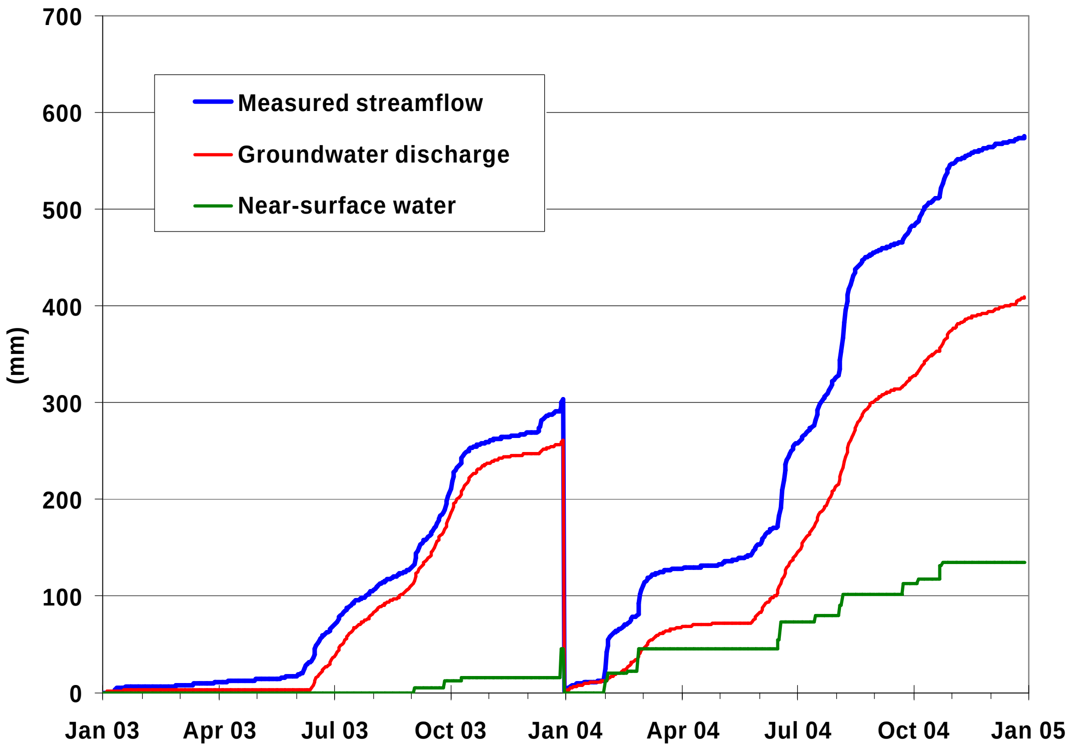

Figure 2. ***Separation of streamflow into groundwater discharge and near-surface water for the years 2003 and 2004 as calculated using the groundwater discharge model.***

Table 5 shows the modelled flowpath contributions to total streamflow in 2003 and 2004. Streamflow in 2003 was amongst the lowest on record, while the streamflow in 2004 is close to the upper limit of recorded annual streamflows. For 2003, groundwater discharge contributed 261mm to the 306mm modelled streamflow (85%) and only 45mm came from near-surface pathways. In 2004, 411mm of the 545mm modelled streamflow came from groundwater discharge (75%) and 134 mm were derived from near-surface pathways (Fig. 2). There is reasonable agreement between modelled and measured total streamflows in both years.

Table 5. ***Groundwater discharge model predictions (mm) of flowpath contributions to total streamflow.***

Year	Groundwater discharge	Near-surface drainflows	Predicted streamflow	Measured streamflow
2003	261	45	306	303
2004	411	134	545	575

Quantification of N fluxes through the groundwater and near-surface pathways

The current state of this work in progress is subsequently demonstrated on the example of the years 2003 and 2004. Using a regression equation calculated by Wilcock et al. (1998), the NO_x-N export through Toenepi Stream can be estimated based on the measured streamflow as 10.0 kg ha^{-1} for the year 2003. According to our groundwater discharge modelling, groundwater contributed 85% of the streamflow. If we assume that the arithmetic mean of all our groundwater data (one outlier excepted, Table 2) best represents the NO_x-N concentration of groundwater discharging into Toenepi Stream, then groundwater discharge would contribute only 1.6 kg ha^{-1} yr^{-1} or 16% to the estimated NO_x-N export of 10.0 kg ha^{-1} yr^{-1}. The average NO_x-N concentration of all near-surface pathways would have to be 18.5 mg L^{-1}, a concentration well above the concentrations we measured in subsurface and surface drains. Effluent-pond discharge has been estimated as contributing 2.9 kg ha^{-1} yr^{-1} NO_x-N. Taking this point-source out of the equation would still require all remaining flowpaths to have an average concentration of 12.1 mg L^{-1}. Using the same assumptions as above, the estimated NO_x-N export amounted to 22.6 kg ha^{-1} in 2004, as a result of the higher streamflow. Modelled groundwater discharge accounted for 71% of the measured streamflow, but only 12% of the estimated NO_x-N export. As in 2003, the NO_x-N concentrations in near-surface water would have to be well above the measured range to explain the calculated NO_x-N export. There is clearly a conundrum between the calculated NO_x-N export and the estimated NO_x-N input into Toenepi stream as estimated by combining the monitoring data with groundwater discharge modelling.

Several possible reasons for this discrepancy have been identified and are going to be addressed during the next project phase. Firstly, the groundwater monitoring transects, which are concentrated in the lowest-lying areas near surface waters, may not be representative for the whole catchment. Secondly, very strong shortlived water table responses to rain have been observed during winter 2004 in some additional wells that were equipped with automated water level recorders. It is conceivable that substantial amounts of nitrate are washed out of the soil zone during these episodic events. Similarly, drainage water nitrogen concentrations could be higher during episodic high flow events, which are underrepresented in the monthly sampling scheme. Finally, it needs to be ascertained whether the regression equation of Wilcock et al. (1998) is still applicable to current conditions.

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